Phenomenology of Charmless Hadronic B Decays

Denis Suprun
University of Chicago

Thanks to C.-W. Chiang, M. Gronau, Z. Luo, J. Rosner
for enjoyable collaborations

Motivation

- B factories have produced a lot of excitement, particularly in measuring indirect CPV in the B system
- $\sin 2\beta = 0.736 \pm 0.049$ from ψK_S based upon BaBar's 81 fb^{-1} and Belle's 140 fb^{-1} data (LP03)

  ⇒ era of precision measurement
- $\sin 2\beta$ can also determined using other modes: ϕK_S, $\eta' K_S$, $K_S K^+ K^-$

- We also want to observe direct CPV in B system and to check whether it is consistent with SM expectation

  BaBar announced first observation of direct CPV:

  $A_{CP}(\pi^- K^+) = -0.133 \pm 0.030 \pm 0.009$ at 4.2σ level
- Most branching ratios of charmless $B \rightarrow PP$ and PV are currently measured with errors about 10%~20%

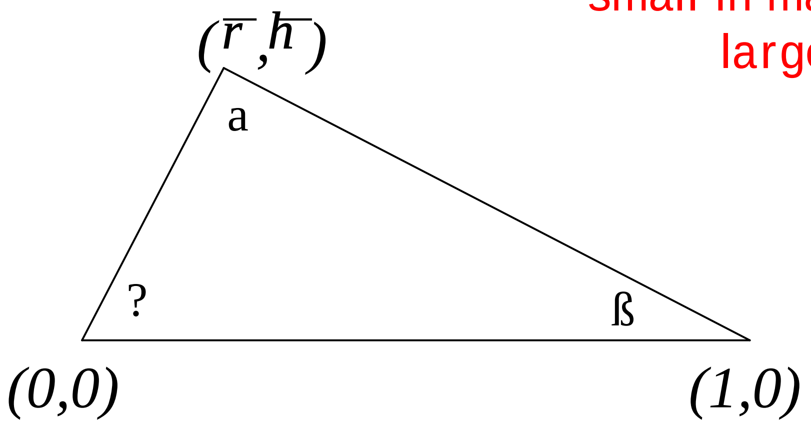
  ⇒ 5%~10% errors in amplitude
- One hopes to have <5% errors on the amplitudes of most modes

  ⇒ more precise information on α and γ ($<10^o$)

CKM Matrix and Unitarity Triangle

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{l^2}{2} & l & A l^3(r - ih) \\ -l & 1-\frac{l^2}{2} & A l^2 \\ A l^3(1-\bar{r}-i\bar{h}) & -A l^2 & 1 \end{bmatrix}$$

small in magnitude but contain largest CPV phases



$$\bar{r} = r(1-\frac{l^2}{2})$$

$$\bar{h} = h(1-\frac{l^2}{2})$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

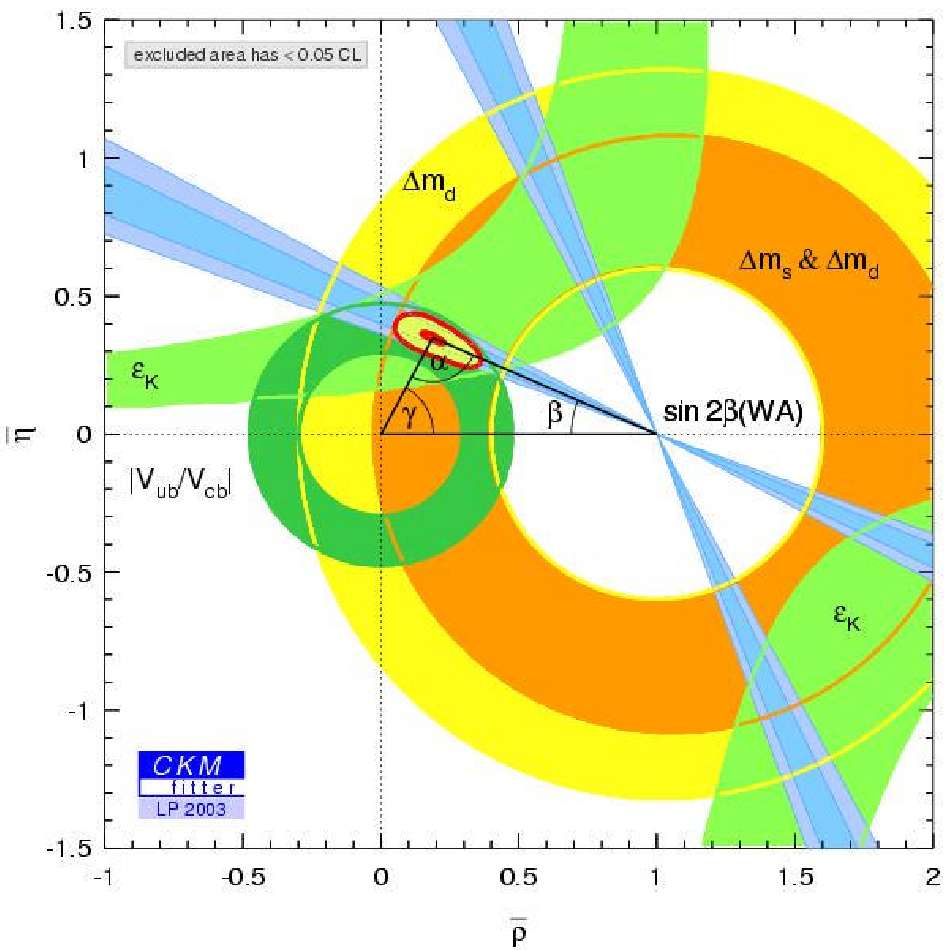
CKM Matrix and B Physics

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{l^2}{2} & l & A\,l^3(r-ih) \\ -\,l & 1-\frac{l^2}{2} & A\,l^2 \\ A\,l^3(1-\bar{r}-i\bar{h}) & -\,A\,l^2 & 1 \end{bmatrix}$$

~ $e^{-iß}$ ~ $e^{-i?}$

- Many B decays involve the two CKM elements of interest to us and may reveal CP violating effects
- The ultimate goal of studies in B physics is not only to achieve precision measurements of the above parameters, but to discover New Physics
- One way to detect New Physics is to perform consistency checks for the sizes and phases of the CKM elements

CKM Fitter results



Parameter	≥ 32% CL range	≥ 32% CL half-width	≥ 5% CL range	≥ 5% CL half-width
λ	0.2279 ± 0.0032		$^{+0.0062}_{-0.0070}$	
A	0.768 - 0.824	0.028	0.746 - 0.864	0.059
$\bar{\rho}$	0.118 - 0.273	0.078	0.071 - 0.332	0.131
$\bar{\eta}$	0.305 - 0.393	0.044	0.259 - 0.419	0.080
J $[10^{-5}]$	2.66 - 3.44	0.39	2.27 - 3.68	0.70
$\sin 2\alpha$	−0.61 - 0.23	0.42	−0.87 - 0.45	0.66
$\sin 2\beta$	0.690 - 0.726	0.036	0.647 - 0.789	0.071
α	83° - 109°	13°	77° - 120°	22°
β	21.8° - 24.8°	1.5°	20.2° - 26.0°	2.9°
γ	48° - 73°	12°	39° - 80°	21°
$\sin\theta_{12}$	0.[illegible]	[illegible]	[illegible]	0.0066
$\sin\theta_{13}$ $[10^{-3}]$	[illegible]	[illegible]	[illegible]	0.41
$\sin\theta_{23}$ $[10^{-3}]$	[illegible]	[illegible]	[illegible]	1.7
V_{ud}	[illegible]	[illegible]	[illegible]	
V_{us}	[illegible]	[illegible]	[illegible]	
V_{ub} $[\times 10^{-3}]$	[illegible]	[illegible]	[illegible]	0.41
V_{cd}	0.2245 - 0.2309	0.0032	0.2206 - 0.2340	0.0067
V_{cs}	0.9729 ± 0.0007		± 0.0015	
V_{cb} $[\times 10^{-3}]$	40.5 - 42.3	0.9	40.0 - 43.4	1.7
V_{td} $[\times 10^{-3}]$	7.38 - 9.02	0.82	6.70 - 9.50	1.40
V_{ts} $[\times 10^{-3}]$	39.8 - 41.7	0.9	39.3 - 42.8	1.8
V_{tb}	0.99910 - 0.99917	0.00004	0.99905 - 0.99919	0.00007
Δm_s $[ps^{-1}]$	16.2 - 24.6	4.2	15.1 - 30.6	7.7
Δm_s $[ps^{-1}]$ (without exp. limit)	12.3 - 26.6	7.1	10.2 - 31.4	10.6
$\mathcal{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$ $[10^{-11}]$	2.1 - 3.5	0.7	1.5 - 4.0	1.2
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ $[10^{-11}]$	6.9 - 9.0	1.1	5.9 - 10.1	2.1
$\mathcal{B}(B^+ \to \mu^+ \nu_\mu)$ $[10^{-7}]$	3.3 - 5.6	1.1	2.8 - 7.3	2.3
$\mathcal{B}(B^+ \to \tau^+ \nu_\tau)$ $[10^{-5}]$	8.5 - 14.1	2.8	7.2 - 18.5	5.7
$f_{B_d}\sqrt{B_d}$ (MeV)	196 - 243	24	187 - 272	43
B_K	0.58 - 1.15	0.28	0.51 - 1.45	0.47
m_t (GeV$/c^2$)	118 - 212	47	102 - 271	85

Numerical results of the Standard CKM fit.

$$s(g) = 12^{0}$$

Upper limit on ? will become more strict when Run II of the Tevatron will become sensitive to B_s oscillations at the level of ?m_s=15 ps^{-1}

Charmless B decays

- Relatively rare decays with branching ratios of the order 10^{-5}
- Wealth of new increasingly precise measurements
- Many of them involve interference of a tree and a penguin amplitude with a weak phase ***?*** between them
- Nonzero (mod ***p***) strong phases are required for *CP* Violation

Are well suited to

- constrain ***?***
- determine the magnitude of penguin contributions
- get some information on strong phases

Importance of Strong Phases

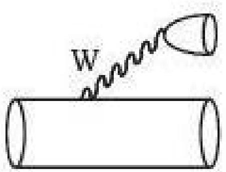
- Consider rate CP asymmetry of modes with the amplitudes

$$A(B \to f) = a_1 e^{i(\phi_1+\delta_1)} + a_2 e^{i(\phi_2+\delta_2)}$$
$$A(\overline{B} \to \overline{f}) = a_1 e^{i(-\phi_1+\delta_1)} + a_2 e^{i(-\phi_2+\delta_2)}$$
$$a_{CP} = \frac{\Gamma(\overline{B} \to \overline{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \overline{f}) + \Gamma(B \to f)} = \frac{2\boxed{a_1 a_2 \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)}}{a_1^2 + a_2^2 + 2a_1 a_2 \cos(\phi_1 - \phi_2)\cos(\delta_1 - \delta_2)}$$

- Such an asymmetry requires at least two amplitudes characterized by distinct weak phases and strong phases
- It is therefore of great importance to understand the patterns of strong FSI phases in as wide as possible a set of decays
- No method for computing FSI strong phases from first principles exist because they involve nonperturbative long-distance physics
- Flavor topology approach offers a way to extract strong phases associated with individual topological amps and enables us to relate them using flavor SU(3) symmetry

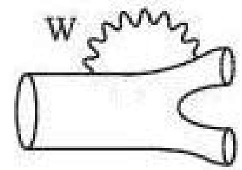
$B \to VP$ decays

Dominant types of amplitudes

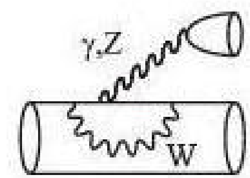


Tree (T)

Color-suppressed (C)



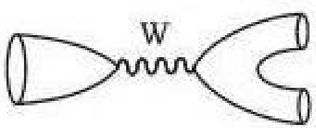
Penguin (P')



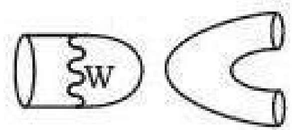
EW penguin (P'_{EW})

Neglect

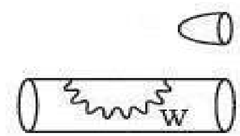
Exchange (E)



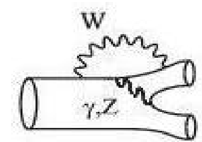
Annihilation (A)



Penguin annihilation (PA)



Singlet penguin (S)



Color-suppressed EW penguin (P'^{C}_{EW})

Assumptions

- The only deviation from SU(3) is through decay constants in tree diagrams
- SU(3) is implied when we assume
  - the same phases for $\boldsymbol{t}$ and $\boldsymbol{t'}$
  - that QCD and EW penguins $\boldsymbol{P'}$ and $\boldsymbol{P}$ and color-suppressed amplitudes $\boldsymbol{C'}$ and $\boldsymbol{C}$ are related to each other as the ratio of the involved CKM parameters
  - that a penguin in which a gluon couples to $s\bar{s}$ has the same amplitude as those that couple to $u\bar{u}$ and $d\bar{d}$

Approach

- Take all available information on charmless *B* decays to a *VP* final state and fit it with a simple model of interference between appropriate tree and penguin diagrams
- Extract magnitudes and relative phases of tree and penguin amplitudes
- Predict branching ratios and *CP* asymmetries for observed and as-yet-unseen modes

- Considerable sensitivity to ?.

Conservative statistical errors

- **Take account of the PDG scaling factor S when BaBar and Belle values are disparate.** S is a measure of discrepancy between several measurements.

- **S(fK$_S$) problem**.

  S(fK$_S$) is predicted to be equal to sin2ß=0.74±0.05, as measured in J/? K$_S$ decays. However, BaBar and Belle measurements of S(fK$_S$) are quite different:

  BaBar: S(fK$_S$) = 0.47±0.34±0.07

  Belle: S(fK$_S$) = -0.96±0.50±0.10.

  Belle claims that the value of 0.74 is excluded at 3.5s confidence level. The world average is

  WA: S(fK$_S$) = 0.02±0.29

  but when S factor is taken into account

  WA: S(fK$_S$) = 0.02±0.66 (S=2.33).

  With the uncertainty being too large, it is too early to say that there is a clear problem with the SM description of the fK$_S$ decay.

- **It is not the only measurement where BaBar and Belle disagree**. Others include

  S(p$^+$p$^-$) with S=1.91

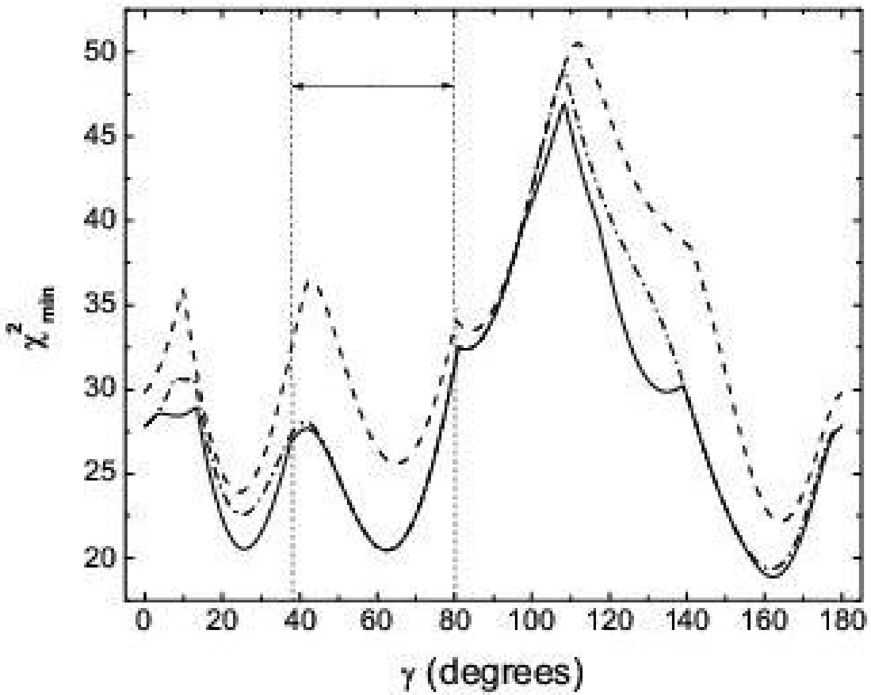
  ? S(?p) with S=2.00

Data and Fit Parameters

- 34 data points:
  - branching ratios and *CP* asymmetries in
    - ✓ strangeness-preserving ***?p, ??, ??¢, ? p*** decays (***? S=0***)
    - ✓ strangeness-changing ***K**p, K*?, K*?¢, ?K, ? K, f K*** decays (***? S=1***)
  - direct and mixing-induced asymmetries in $\boldsymbol{?^{\pm}p^{\mp}}$ and $\boldsymbol{f K_S}$ decays

- 12 fit parameters:
  - weak phase ***?***
  - amplitudes: $|t_P|$, $|t_V|$, $|C_P|$, $|C_V|$, $|P^{¢}_P|$, $|P^{¢}_V|$, $|P^{¢}_{EW,P}|$, $|P^{¢}_{EW,V}|$
  - strong phases: d_V, d_P, f

?^{2}-? plot



Three minima of about equal depth: ***?=26^o, 63^o, 162^o***
Ambiguity can not be resolved from the *B®VP* data alone.

Appeal to experiment:
CKM Fitter: ***39^o<?<80^o***

Appeal to theory:
Minima at ***26^o*** and ***162^o*** feature large strong phases leading to
Arg(t_P/t_V)=-(87±10)^o and
(38±12)^o,
respectively.
Arg(t_P/t_V)=-(20±10)^o at ***?=63^o***

?=(63±6)^o: *Fit quality 55%*

Predictions

- **Largest predicted *CP* asymmetries:**

  $A_{CP}(?^0 p^+)$=-0.16±0.04 $A_{CP}(?^0 K^+)$=0.21±0.10

  $A_{CP}(?^- p^+)$=-0.13±0.06 $A_{CP}(?^- K^+)$=0.16±0.07

  $A_{CP}(?\ K^+)$=0.19±0.08

- **As yet unseen modes to be observed soon (in 10^{-6}):**

Predicted br. ratios:	*Current UL*
$B(K^{*+} p^0)$=15.0±3.1	<31
$B(?^0 K^0)$=7.2±2.0	<12.4
$B(?^+ K^0)$=12.6±1.6	<48

$?^+K^0$ is a pure $p^{¢}_V$ penguin and its measurement is particularly important

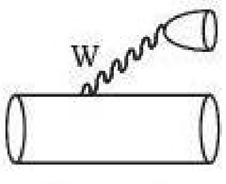
Comments on SU(3)

- In the last few months I saw new and more precise measurements shifting closer to our predictions.
- Despite smaller errors the quality of the fit improved: ?^{2} dropped by 1.8 units to 18.7/22. Fit parameters remained stable.
- Probably, we can not yet see significant SU(3) breaking effects in the current *B VP* data.
- I expect that the predictions of this method will remain reliable for at least another year.

- Recent BaBar measurement of B(B^0 ? ?)=4.0±1.6 is a challenge.

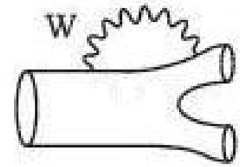
B PP decays

Dominant types of amplitudes

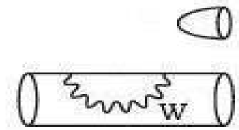


Tree (T)

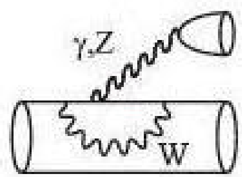
Color-suppressed (C)



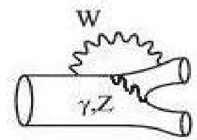
Penguin (P¢)



Singlet penguin (S)



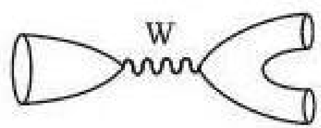
EW penguin (P¢$_{EW}$)



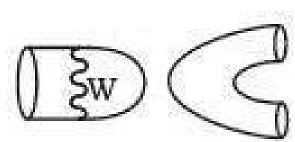
Color-suppressed EW penguin (P'^{C}_{EW})

Neglect

Exchange (E)



Annihilation (A)



Penguin annihilation (PA)

pp, Kp Fit

- A nonzero relative strong phase *dC* between tree *T* and color suppressed *C* amplitudes is the key to getting a good fit.
- It doesn't lead to predictions of large CP asymmetries in the modes where we didn't expect them before. For example, p^+p^0 decays ($t+c$) are still predicted to have zero CP asymmetry because of zero weak phase difference between *t* and *c* amplitudes.
- With *dC* we can get a good fit to all pp, Kp decay modes: ?^{2}=7.34/8, fit quality: 50%.
- Problem: |C/T|=1.4.

P_{tu} as a solution to the large |C/T| problem

- Penguins that feature b d, b s transitions can be mediated by u, c, or t quarks. For the b d case the corresponding CKM matrix elements are $V^*_{ub}V_{ud}$, $V^*_{cb}V_{cd}$, and $V^*_{tb}V_{td}$. Typically, one uses the unitarity relation to replace $V^*_{tb}V_{td} = -V^*_{cb}V_{cd} - V^*_{ub}V_{ud}$ an write a “pure” penguin as

$$p = V^*_{cb}V_{cd}\, P - V^*_{ub}V_{ud}\, P_{tu}.$$

- Original versions of the fit neglected the second term. Note that it features the same CKM matrix elements as a tree or a color-suppressed amplitude. Thus, P_{tu} can disguise itself as a part of T or C.
- When P_{tu} is not explicitly used as a parameter in p^0p^0 (c-p) and p^+p^- (t+p) decay modes, this may lead to a larger C and a smaller T amplitude because they invisibly include P_{tu} contributions.

P_{tu} as a solution to the large |C/T| problem

- Now use P_{tu} and its strong phase dP_{tu} (with respect to P) as fit parameters.
- P_{tu} was found to be of about the same size as P.
  - In b   s transitions its influence is much less prominent for two reasons:

    (a) P' term is larger than P by $|V_{cs}/V_{cd}|$ » ?

    (b) P'_{tu} term is smaller than P_{tu} by $|V_{us}/V_{ud}|$ » ?
- P_{tu} interferes constructively with C and destructively with T. Now that P_{tu} was explicitly taken into account, |C/T| went down to a more reasonable |C/T|=0.46.
- dP_{tu} was found to be very small, just 3°.
  - The "pure" penguin modes (K^+K^0bar, K^0K^0bar, p^+K^0) are actually an interference of P and P_{tu} with a weak phase difference ? between them. Due to small strong phase difference dP_{tu}, CP asymmetry in these decays is still expected to be small.

B pK Puzzle

- **From experiment** Br(B p^-K^+) / 2Br(B p^0K^0) = 0.76±0.10

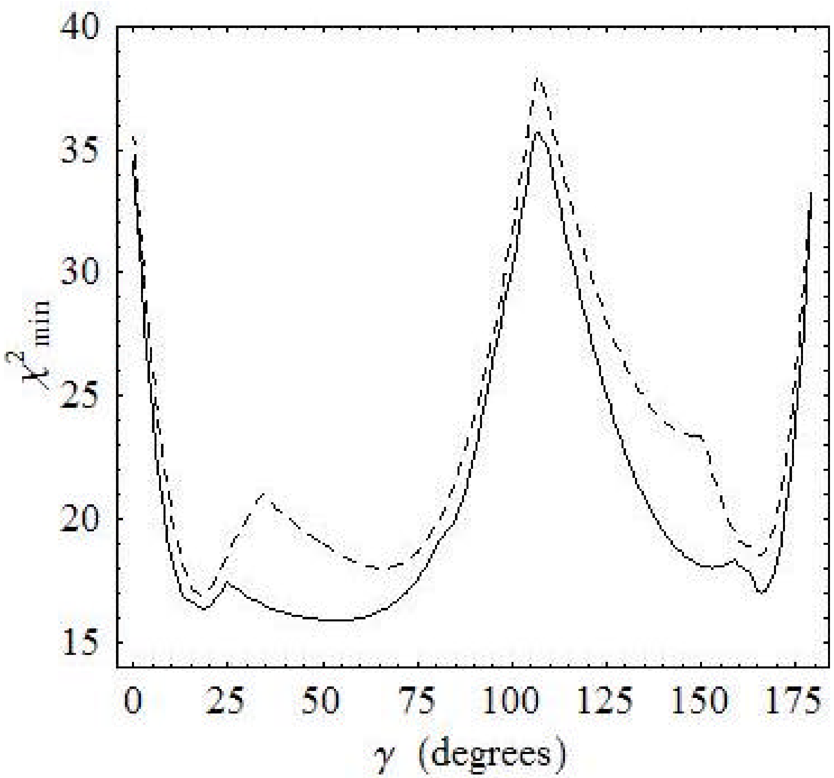
  while it is expected to be around 1.
- Buras, Fleischer, Recksiegel, Schwab solution:
  - Solve B pp system by neglecting EWPs. Extract T, C, P and strong phases.
  - Scale the values of amplitudes and phases to get T', C' and P' using SU(3) flavor symmetry and CKM parameters.
  - Use them and **enhanced** EW penguins with **a large CP-violating New Physics phase** to get a good description of pK data.
- Our approach is less radical and is within the SM. We don’t use any NP parameters. We manage to get a good fit which adequately describes both pp and pK data simultaneously (without being a precise solution to any of the two subsets). The fit doesn’t give a good “prediction” for Br(B p^0K^0) (deviation 1.7s) but the fit quality (50%) implies that the SM still gives an adequate description of pp, pK data.

Data and Parameters of the Full PP Fit

- 26 data points:
  - branching ratios and *CP* asymmetries in
    - ✓ strangeness-preserving ***pp*, *p?*, *p?*¢** decays (***?S=0***)
    - ✓ strangeness-changing ***Kp*, *K?*, *K?*¢** decays (***?S=1***)
  - direct and mixing-induced asymmetries in $\boldsymbol{p^{+}p^{-}}$, $\boldsymbol{p^{0}K_{S}}$ and $\boldsymbol{?^{¢}K_{S}}$ decays

- 13 fit parameters:
  - weak phase ***?***
  - amplitudes: $|\boldsymbol{T}|$, $|\boldsymbol{C}|$, $|\boldsymbol{P^{¢}}|$, $|\boldsymbol{P_{tu}}|$, $|\boldsymbol{S^{¢}}|$, $|\boldsymbol{S_{tu}}|$
  - strong phases: $\boldsymbol{d_{T}}$, $\boldsymbol{d_{C}}$, $\boldsymbol{dP_{tu}}$, $\boldsymbol{d_{S}}$, $\boldsymbol{dS_{tu}}$
  - $\boldsymbol{d_{EW}}$ factor that relates EW penguins to tree-level diagrams

?^{2}-? plot



Three minima of about equal depth. Ambiguity can not be resolved from the *B®PP* data alone.

Appeal to experiment:
CKM Fitter: ***39^o<?<80^o***

Fit without $\boldsymbol{S_{tu}}$: ?^{2}=18.1/15; *?=(66±14)^o*

Fit with $\boldsymbol{S_{tu}}$: ?^{2}=16.0/13; *?=(54±21)^o*

Predictions for some B_s decays

- CDF blessed measurement:

$$Br(B_s \quad K^+K^-) / Br(B_d \quad K^+p^-) = 2.71\pm0.73\pm0.35\pm0.81$$
$$= 2.71\pm1.15$$

We predict:

$$Br(B_s \quad K^+K^-) / Br(B_d \quad K^+p^-) = 0.93$$

- CDF preliminary result (presented at APS):

$$Br(B_s \quad K^-p^+) \sim 10\cdot10^{-6}$$

We predict:

$$Br(B_s \quad K^-p^+) = 4.2\cdot10^{-6}$$

- Predictions for all B_s charmless hadronic decay modes will appear in a paper to be posted on the Net next month.

Summary and Outlook

- Flavor nonet symmetry is employed to analyze B decays into VP and PP final states; symmetry breaking effect is partially taken into account for tree amplitudes.
- Flavor SU(3) generally fits data well, with some exceptions. Predictions are made based upon current measurements.
- Our preferred $\gamma \approx 63^o$ fit in VP modes favors a weak phase γ within the range 57^o-69^o at 1σ level and 51^o-73^o at 95%CL. It is compatible with other determinations of γ.
- Our preferred $\gamma \approx 54^o$ fit in PP modes favors a weak phase γ within the range $30^o \sim 72^o$ at 1σ level. It is also compatible with the CKM Fitter favored γ range: ***39º<?<80º***
- Expect B_s decays to be measured at Tevatron Run II. Predictions on the branching ratios and CP asymmetries can be made on the basis of SU(3) flavor symmetry and the magnitudes and phases of the topological diagrams extracted from B_d decays to PP and VP final states.